FIBER-OPTIC WAVEGUIDES FOR EVANESCENT OPTICAL COUPLING AND METHODS OF FABRICATION AND USE THEREOF

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FIELD OF THE INVENTION

The field of the present invention relates to optical fiber telecommunications and sensors. In particular, apparatus and methods are described herein for evanescent optical coupling of an optical fiber to a whispering-gallery-mode optical resonator or other optical waveguide and/or resonator.

BACKGROUND

This application is related to subject matter disclosed in:

A1. U.S. provisional Application No. 60/111,484 entitled "An all-fiber-optic modulator" filed 12/07/1998 in the names of Kerry J. Vahala and Amnon Yariv, said provisional application being hereby incorporated by reference in its entirety as if fully set forth herein;

A2. U.S. Application No. 09/454,719 entitled "Resonant optical wave power control devices and methods" filed 12/07/1999 in the names of Kerry J. Vahala and Amnon Yariv, said application being hereby incorporated by reference in its entirety as if fully set forth herein;

A3. U.S. provisional Application No. 60/108,358 entitled "Dual tapered fiber-microsphere coupler" filed 11/13/1998 in the names of Kerry J. Vahala and Ming Cai, said provisional application being hereby incorporated by reference in its entirety as if fully set forth herein;

A4. U.S. Application No. 09/440,311 entitled "Resonator fiber bi-directional coupler" filed 11/12/1999 in the names of Kerry J. Vahala, Ming Cai, and Guido Hunziker, said application being hereby incorporated by reference in its entirety as if fully set forth herein; and

A5. U.S. provisional Application No. 60/183,499 entitled "Resonant optical power control devices and methods of fabrication thereof" filed 02/17/2000 in the names of Peter C. Sercel and Kerry J. Vahala, said provisional application being hereby incorporated by reference in its entirety as if fully set forth herein.

This application is also related to subject matter disclosed in the following seven publications, each of said seven publications being hereby incorporated by reference in its entirety as if fully set forth herein:

P1. "Fiber-optic add-drop device based on a silica microsphere whispering gallery mode system", Ming Cai, Guido Hunziker, and Kerry Vahala, IEEE Photonics Technology Letters Vol 11 686 (1999);

P2. "Phased-matched excitation of whispering gallery-mode resonances by a fiber taper", J. C. Knight, G. Cheung, F. Jacques, and T. A. Birks, Optics Letters Vol. 22 1129 (1997);

P3. "Excitation of resonances of microspheres on an optical fiber", Serpenguzel, S. Arnold, and G. Griffel, Optics Letters Vol. 20, 654 (1995);

P4. "Microlasers based on silica microspheres", F. Treussart, N. Dubreil, J. C. Knight, V. Sandoghar, J. Hare, V. Lefevre-Seguin, J. M. Raimond, and S. Haroche, Ann. Telecommun. Vol. 52, 557 (1997);

P5. "Ultimate Q of optical microsphere resonators", M. L. Gorodetsky, A. A. Savchenkov, V. S. Ilchenko, Optics Letters, **21**, 453 (1996);

P6. "Observation of critical coupling in a fiber taper to a silica-microsphere whispering-gallery mode system", Ming Cai, Oskar Painter, and Kerry J. Vahala,, Physical Review Letters Vol 85, 74 (2000); and

P7. "Whispering-gallery mode microdisk lasers", S. L. McCall, A. F. J. Levi, R. E. Slusher, S. J. Pearton, and R. A. Logan, Applied Physics Letters Vol. 60, 289 (1992).

Optical fiber and propagation of high-speed optical pulses therethrough has become the technology of choice for high speed telecommunications. Wavelength division multiplexing (WDM) techniques are now commonly used to independently transmit a plurality of signals over a single optical fiber, each independent data stream being carried by a slightly different optical carrier wavelength. Signal carried by individual channels must be independently accessible for routing from a particular source to a particular destination. This has previously required complex and difficult-to-manufacture switching devices requiring extensive active alignment

procedures during fabrication/assembly, and as a result are expensive. Such devices may require conversion of the optical signals to electronic signals and back again, which can be power consuming and inefficient. In the patent applications cited above a new approach has been disclosed for controlling optical power transmitted through an optical fiber that relies on the use of resonant whispering-gallery-mode (hereinafter "WGM") optical resonators for direct optical coupling to an optical fiber, thereby enabling wavelength-specific modulation and/or routing of optical signals propagating through the optical fiber and the substantial elimination of conventional fiber coupling and/or packaging procedures. A thorough discussion of the features and advantages of such optical power control devices and techniques, as well as methods of fabrication, may be found in these applications, already incorporated by reference herein.

One of the modern design goals of fiber optic communications has been that, to the greatest extent feasible, components and/or devices should keep the light wave signal in optical fiber. This is based on the common sense observation that to couple light from a device into optical fiber or vice versa is expensive and typically introduces undesirable loss. Fiber Bragg filters and erbium fiber optical amplifiers are technologies that exemplify successful realizations of this goal. Other examples more directly relevant to this disclosure are optical power control devices, including all-fiber-optic modulators and/or all-fiber channel add-drop filters (described in the patent applications cited hereinabove and incorporated by reference herein). An important element of these latter devices is efficient coupling to whispering-gallery-mode optical resonators using a single-mode optical fiber in which a tapered section has been prepared as an evanescent optical coupling portion thereof. The taper is fabricated by heating a portion of the fiber in a flame while pulling the unheated fiber sections to either side of this portion in opposing directions to achieve a narrow (typically 1-5 microns) neck. Alternatively the fiber may be heated by other means such as a exposure to the emission from a CO_2 laser while pulling the unheated sections apart longitudinally. A WGM optical resonator structure such as a glass micro-sphere or micro-disk is then positioned near the fiber taper and evanescent optical coupling between the WGM resonator and the fiber taper waveguide results (through spatial overlap of an evanescent portion of the propagating optical mode extending outside the taper and an evanescent portion of a whispering-gallery optical mode extending beyond the WGM resonator). Alternatively the tapered optical fiber may be similarly coupled to whispering-gallery modes of fiber-ring resonators as described in U.S. provisional Application No. 60/183,499 cited hereinabove. Since the tapered optical fiber and the WGM optical resonator

structure may be made of the same, or nearly the same, material, optical phase matching is facilitated, thereby enabling efficient optical coupling between a single propagating optical mode of the optical fiber taper waveguide and a whispering-gallery optical mode of the WGM optical resonator.

The use of tapered optical fiber as a waveguide member for optically coupling to a WGM optical resonator has several advantages over the conventional prism-coupling scheme for coupling to WGM resonators (as disclosed, for example, by Gorodetsky et al, cited hereinabove). These advantages include: 1) No sophisticated optical coupling assembly is required as input and output light is always guided and manipulated in optical fiber; 2) Insertion losses into/out of tapered single mode fiber can be extremely low and spectrally nearly uniform (for example, personnel at Aleph Lightgate have routinely demonstrated taper insertion losses as low as 0.1 dB); 3) The Vahala group at Caltech has shown that even when a silica WGM resonator structure such as a micro-sphere is in contact with a taper, the WGM resonator may exhibit a Q-factor in excess of 10^6, thereby eliminating in certain cases the need for sophisticated sub-micron piezoelectric actuators; and 4) The system is inherently robust owing to its all fiber optic construction.

There are, however, several problems with the use of tapered optical fiber waveguides for optical coupling to WGM optical resonators (such as micro-spheres, micro-disks, micro-rings, and/or fiber rings) or to other optical waveguide and/or resonators. These include:

A. *Difficulty in producing polarization maintaining tapered fiber:*

It is difficult to prepare fiber-optic tapers using polarization-maintaining (PM) optical fiber. In many applications of optical power control devices in telecommunications or sensor applications, it is important to use PM fiber, since resonant whispering-gallery optical modes in spheres, disks, and rings are generally polarization dependent, as are optical modes of other optical waveguides and/or resonators. PM fiber is necessary to guarantee that optical power may be launched into the taper with a suitably specified polarization state, so as to couple to a particular whispering-gallery optical mode of the WGM resonator structure, for example. Such PM fiber, including standard bowtie or panda (shown in cross-section in Fig. 1) fiber designs, is fabricated with internal longitudinal stressor elements 105 surrounding the core 104, the stressor elements typically being composed of doped silicate glass (e.g., borosilicate glass) having mechanical properties and/or melting point substantially differing from the surrounding silica

cladding 106. Thus when the PM fiber 100 is heated and pulled, the stressor rods and the surrounding cladding material melt at different points and the tapered fiber structure produced has unacceptably high insertion loss (typically 20dB), arising from both structural irregularities in the tapered fiber (due to the inhomogeneous structure) and optical coupling from the guided fiber core optical mode into optical modes of the stressor rods themselves.

A possible solution to this problem of fabricating PM fiber tapers would be splicing a section of standard fiber (i.e., non-polarization-maintaining fiber, having a substantially homogeneous cladding layer with no stressor elements) into a length of PM fiber and pulling the tapered section in the standard fiber segment. Provided the spliced-in section is sufficiency short, an optical mode propagating through the tapered segment should experience minimal randomization of polarization. However, the two opposing sections of PM fiber must be rotationally aligned to high precision (1° or better), which represents a significant manufacturing problem if the spliced-in standard fiber segment has any appreciable length (greater than about 1 mm, for example).

B. *Difficulty in handling and assembling structures containing tapered fiber due to the fragility and flexibility of tapers:*

Tapered optical fibers, in order to be useful as evanescent optical coupling members for wavelength bands currently most relevant to fiber-optic telecommunications (about 1.2 μm to about 1.7 μm), must be prepared with a taper diameter of about 1-3 μm, and are consequently extremely flexible. Thus for example, even when the non-tapered sections of a tapered fiber are placed coaxially in an alignment groove, the tapered section may sag or bow so that it is not positioned coaxially with respect to the non-tapered sections. This renders problematic the production of mechanically rigid, stable assemblies comprising micro-spheres, micro-rings, micro-disks, fiber rings, and/or other WGM resonator structures and the tapered optical fiber waveguide member. Also, by virtue of the small diameter, a tapered optical fiber is extremely fragile. It is therefore difficult to place, without breakage, the fiber taper within an alignment fixture such as a groove machined into a rigid substrate, as described for example in U.S. provisional Application No. 60/183,499 cited hereinabove.

For these reasons it may be considered preferable to use a "D"-shaped optical fiber as a waveguide coupling member instead of an optical fiber taper as shown in Fig.2. In such a D-fiber 200, the fiber has a D-shaped cross-section such that the fiber core 202 is sufficiently near

to the flat side of the "D" that an optical mode propagating along the fiber has an evanescent wave portion extending transversely beyond the flat side of the "D". Upon assembly of an optical power control device, the D-shaped transmission optical fiber and the WGM resonator structure 204 may each be positioned and secured in respective alignment grooves and so that the WGM resonator structure is in substantial tangential engagement (in mechanical contact, for example) with the flat portion of the "D". As described earlier in U.S. provisional Application No. 60/183,499, appropriate depths of the alignment grooves of a substrate, along with mating alignment structures on adjacent fiber segments and the resonator-alignment grooves may be employed to enable reproducible, reliable, and stable optical coupling of the WGM and the D-shaped transmission fiber without resort to complicated and/or labor-intensive active alignment procedures. Advantages of this approach are: 1) mechanical stability and ease of placement of the D-fiber coupling member; 2) D-fibers which are polarization maintaining are commercially available (e.g. from KVH Industries, Inc.).

There is however one significant disadvantage to the use of D-shaped fiber: it is difficult to achieve a low-loss, mechanically robust fusion splice between D-fiber and ordinary optical fiber of substantially circular cross-section, either PM or standard. This disadvantage translates into increased manufacturing costs and degraded performance (particularly insertion loss) of any device such as a modulator, add-drop filter, or sensor that is based on optical coupling between a WGM optical resonator structure and a D-fiber. One means for circumventing this difficulty is use of a standard fiber or PM fiber of circular cross-section and mechanically polishing a flat surface parallel to the fiber axis so as to achieve a D-shaped cross section over a finite length of the fiber. This means was disclosed in publications 3) and 4) cited hereinabove. While this technique has been shown to be effective in those publications (that is, effective in producing all-fiber members for coupling to WGM structures), it is not a practical manufacturing technique since the mechanical polishing necessary is laborious and difficult to control with precision (the distance between the fiber core and the flat of the "D" must be controlled to sub-micrometer precision in order to achieve reproducible controlled optical coupling between the waveguide and the WGM structure).

It is therefore desirable to provide a fiber-optic waveguide for evanescent coupling to a WGM optical resonator, and methods of fabrication and use thereof, wherein:

The fiber-optic waveguide is mechanically stable and robust, thereby enabling reliable, reproducible, and stable optical coupling between the fiber-optic waveguide and a WGM optical resonator and facilitating handling of the waveguide and fabrication and/or assembly of an optical power control device without excessively frequent breakage of the waveguide.

The fiber-optic waveguide may be readily and reproducibly manufactured, and readily and reproducibly incorporated into an optical power control device using substantially passive alignment techniques.

The fiber-optic waveguide may be readily and reproducibly inserted into polarization-maintaining optical fiber with relatively low insertion loss (less than about 3 dB) using standard optical-fiber splicing techniques.

SUMMARY

Certain aspects of the present invention may overcome one or more aforementioned drawbacks of the previous art and/or advance the state-of-the-art of fiber-optic waveguides for evanescent coupling and optical power control devices, and in addition may meet one or more of the following objects:

To provide a fiber-optic waveguide for evanescent optical coupling;

To provide a fiber optic-waveguide for evanescent optical coupling to a whispering-gallery-mode optical resonator;

To provide a fiber-optic waveguide for evanescent optical coupling that is polarization-maintaining;

To provide a fiber-optic waveguide for evanescent optical coupling that may be readily and reproducibly inserted into polarization-maintaining optical fiber with relatively low insertion loss by standard fiber-optic splicing techniques;

To provide a fiber-optic waveguide for evanescent optical coupling that is sufficiently mechanically robust to enable reliable, reproducible, and stable evanescent optical coupling between the fiber-optic waveguide and a whispering-gallery-mode optical resonator;

To provide a fiber-optic waveguide for evanescent optical coupling that is sufficiently mechanically robust to resist or substantially prevent breakage during handling of the waveguide and/or incorporation of the waveguide into an optical power control device;

To provide a fiber-optic waveguide for evanescent optical coupling wherein a portion of the cladding layer of an evanescent waveguide fiber segment has been removed and the remaining cladding layer material is asymmetrically disposed about the core;

To provide a fiber-optic waveguide for evanescent optical coupling wherein cladding layer material is removed from the evanescent waveguide fiber segment by spatially-selective masking of the cladding layer and etching of the cladding material;

To provide methods for fabricating a fiber-optic waveguide wherein the shape of a coupling portion of the cladding layer surface of the evanescent waveguide portion is adapted to facilitate reliable, reproducible, and stable optical coupling between the waveguide and an optical waveguide and/or resonator;

To provide methods for fabricating a fiber-optic waveguide wherein the shape of a coupling portion of the cladding layer surface of the evanescent waveguide portion is adapted to facilitate reliable, reproducible, and stable optical coupling between the waveguide and a whispering-gallery-mode optical resonator;

To provide a fiber-optic waveguide for evanescent optical coupling adapted to enable reliable, reproducible, and stable optical coupling between the waveguide and a whispering-gallery-mode optical resonator by substantially passive alignment;

To provide a fiber-optic waveguide for evanescent optical coupling fabricated from polarization-maintaining optical fiber;

To provide a fiber-optic waveguide for evanescent optical coupling fabricated from polarization-maintaining optical fiber, wherein the stressor elements of the polarization-maintaining optical fiber extend transversely beyond the cladding layer surface, thereby providing passive alignment structures for enabling passive alignment of the waveguide with a whispering-gallery-mode optical resonator;

To provide methods for fabricating a fiber-optic waveguide for evanescent optical coupling that achieves one or more of the foregoing objects; and

To provide an optical power control device, and methods of fabrication and/or assembly thereof, incorporating a fiber-optic waveguide that achieves one or more of the foregoing objects.

One or more of the foregoing objects may be achieved in the present invention by a fiber-optic waveguide comprising: 1) an evanescent waveguide fiber segment; and 2) first and second longitudinally adjacent fiber segments joined to the ends of the evanescent waveguide fiber segment and having cores that form, with the core of the evanescent waveguide fiber segment, a substantially continuous core of the fiber-optic waveguide. The cladding layers of the adjacent fiber segments substantially surround the cores thereof and substantially transversely encompass an optical mode propagating through the fiber-optic waveguide. The cladding layer of the

evanescent waveguide fiber segment is asymmetrically disposed about at least a portion of the core thereof, thereby yielding a coupling portion of the cladding layer surface and enabling an evanescent portion of the propagating optical mode to extend transversely beyond at least a portion of the coupling portion of the cladding layer surface of the evanescent waveguide fiber segment. The fiber-optic waveguide may be incorporated into an optical power control device by tangentially engaging the coupling portion of the cladding layer surface of the evanescent waveguide fiber segment with a WGM optical resonator, thereby enabling control of optical power transmitted through the fiber-optic waveguide via modulation of WGM resonator properties and/or coupling thereto. The fiber-optic waveguide may be fabricated by circumferentially asymmetric removal of cladding material from the evanescent waveguide fiber segment. The cladding material may be removed by providing a mask for the adjacent fiber segments and a portion of the length and circumference of the evanescent waveguide fiber segment, and etching the cladding layer material.

Additional objects and advantages of the present invention may become apparent upon referring to the preferred and alternative embodiments of the present invention as illustrated in the drawings and described in the following written description and/or claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a transverse-sectional view of standard panda-type polarization-maintaining (PM) optical fiber.

Fig. 2 shows a D-shaped optical fiber (transverse section) in tangential contact with a fiber-ring WGM optical resonator.

Figs. 3A and 3B show side and top views, respectively, of a fiber-optic waveguide according to the present invention.

Figs. 3C and 3D show transverse-sectional views of an adjacent fiber segment and a waveguide fiber segment, respectively, of a fiber-optic waveguide according to the present invention.

Fig. 3E shows a longitudinal-sectional view of a fiber-optic waveguide according to the present invention.

Fig. 4A illustrates a method for fabricating a fiber-optic waveguide according to the present invention.

Figs 4B and 4C show transverse sectional views of an adjacent fiber segment and a waveguide fiber segment, respectively, of a coated optical fiber after laser machining but prior to etching, according to the method for fabrication shown in Fig. 4A.

Fig. 5 illustrates a method for fabricating a fiber-optic waveguide according to the present invention.

Figs. 6A and 6B show longitudinal- and transverse-sectional views, respectively, of a fiber-optic waveguide according to the present invention.

Figs. 7A and 7B show longitudinal- and transverse-sectional views, respectively, of a fiber-optic waveguide according to the present invention.

Figs. 8A and 8B show sectional views of a fiber-optic waveguide coupled to a fiber-ring WGM optical resonator according to the present invention.

Figs. 9A and 9B show sectional views of a fiber-optic waveguide coupled to a "thumbtack" WGM optical resonator according to the present invention.

Figs. 10A and 10B show longitudinal- and transverse-sectional views, respectively, of a fiber-optic waveguide according to the present invention.

Figs. 11A, 11B, and 11C show a fiber-optic waveguide having passive alignment structures and being coupled to a fiber-ring resonator according to the present invention.

Fig. 12 illustrates a method for coupling a fiber-ring WGM optical resonator and a fiber-optic waveguide on an alignment substrate according to the present invention.

Figs. 13A and 13B show sectional views of a fiber-ring WGM optical resonator coupled to a fiber-optic waveguide on an alignment substrate according to the present invention.

Figs. 14A and 14B show sectional views of a fiber-ring WGM optical resonator coupled to a fiber-optic waveguide and sealed within an alignment substrate according to the present invention.

Figs. 15A and 15B show sectional views of a fiber-ring WGM optical resonator coupled to two fiber-optic waveguides and sealed within an alignment device according to the present invention.

Figs. 16A, 16B, and 16C show sectional and top views of a micro-sphere WGM optical resonator coupled to a fiber-optic waveguide and sealed within an alignment substrate according to the present invention.

Fig. 17 illustrates a method for fabricating a fiber-optic waveguide according to the present invention.

It should be noted that the relative proportions of various structures shown in the Figures may be distorted to more clearly illustrate the present invention. In particular, the size differential and resonator thickness may be greatly exaggerated relative to the underlying optical fiber diameter in the Figures for clarity. Various metal, semiconductor, and/or other thin films and/or coatings are also shown having exaggerated thickness for clarity. The text and incorporated references should be relied on for the appropriate dimensions of structures shown herein.

DETAILED DESCRIPTION OF PREFERRED AND ALTERNATIVE EMBODIMENTS

A waveguide optical fiber for transmitting an optical signal (alternatively, a propagating optical mode) to be controlled, modulated, and/or routed is provided with an evanescent waveguide fiber segment 302 between longitudinally adjacent fiber segments 312, as shown generally in Figs. 3A, 3B, 3C, 3D, and 3E. Each of the evanescent waveguide and adjacent fiber segments 302/312 comprises a core 304/314 and a cladding layer 306/316, with the respective cores forming a substantially continuous core of fiber-optic waveguide 300 and enabling propagation of an optical mode therethrough. The cladding layers 316 of the adjacent fiber segments 312 are sufficiently large to substantially transversely encompass the propagating optical mode within the cladding layers. The cladding layer 306 of the evanescent waveguide fiber segment 302 is asymmetrically disposed about the core 304 thereof and forms a coupling portion 308 of the cladding layer surface. An evanescent portion of the propagating optical mode extends transversely beyond the coupling portion 308 of the cladding layer surface of the evanescent waveguide segment 302, thereby enabling evanescent optical coupling to other optical devices/structures, as further described hereinbelow and in the patent applications cited and incorporated by reference hereinabove. The evanescent optical coupling thus achieved in turn enables control, modulation, and/or routing of the optical mode propagating through the fiber-optic waveguide 300. The asymmetric distribution of the cladding layer 306 about the core 304 of the evanescent waveguide fiber segment 302 may typically be achieved by spatially selective removal of cladding layer material from the evanescent waveguide fiber segment.

Single mode optical fiber, including polarization-maintaining (PM) optical fiber, is commonly available commercially having a diameter of about 80 μm or about 125 μm (higher refractive index core plus lower refractive index cladding, excluding any additional jacket material) and a core diameter on the order of about 5 to 10 μm. PM fiber may also include longitudinally extending stressor elements disposed in substantially opposing positions about the core within the cladding layer as shown in Fig.1. Other fiber cladding and core diameters suitable for transmitting the propagating optical mode may be used as well. Spatially-selective and circumferentially asymmetric removal of cladding layer material from an evanescent waveguide fiber segment of an optical fiber (PM or otherwise) yields a fiber-optic waveguide for evanescent optical coupling according to the present invention. Such material removal may

preferably be achieved by spatially-selective and circumferentially asymmetric etching of the cladding layer of the optical fiber.

A preferred method for removing cladding layer material from the evanescent waveguide fiber segment is illustrated generally in Figs. 4A, 4B, and 4C, and comprises the steps of: 1) providing the adjacent fiber segments 312 and a portion of the length and circumference of the evanescent waveguide fiber segment 302 with a mask (shown as stippled shading in Fig. 4A); and 2) spatially-selectively etching the exposed portions of the evanescent waveguide fiber segment 302, thereby yielding an asymmetrically disposed cladding layer 306 about the core 304 and providing a coupling portion 308 of the cladding layer surface. The mask may be removed after etching. This procedure may be contrasted to the methods disclosed in prior provisional Application No. 60/183,499, cited hereinabove, wherein complete (360°) cylindrical rings are machined or otherwise provided in the optical fiber outer coating, resulting in substantially circumferentially symmetric removal of cladding layer material and fabrication of fiber rings. Many optical fibers are supplied with an outer coating comprising a polymer jacket (acrylate, polyimide, or the like), and this jacket may be used as a mask provided it adheres sufficiently to the optical fiber during etching. A preferred mask may comprise a carbon outer fiber coating. Optical fiber having a hermetic carbon outer coating (with or without a polymer jacket over the hermetic carbon coating) may be obtained commercially (Hermeticoat optical fiber, sold by Spectran Specialty Optics) or may be fabricated by deposition of a carbon layer on the fiber cladding (see for example U.S. Patent No. 5,281,247, said patent being hereby incorporated by reference in its entirety as if fully set forth herein). A carbon coating has been found to adhere well to the optical fiber during etching of the optical fiber. Alternatively, the optical fiber may be coated with photo-resist material as the outer fiber coating.

Whether the outer coating comprises a polymer jacket, a carbon film, or a photo-resist, the outer coating must be spatially patterned appropriately, thereby yielding a mask portion 319 substantially covering the adjacent fiber segments 312 and a mask portion 309 covering the desired portions of the evanescent waveguide fiber segment 302 during etching. The mask may preferably be patterned by spatially selective laser machining or laser processing of the outer coating, removing the outer coating only from the desired portions of the length and circumference of the evanescent waveguide fiber segment. A polymer jacket outer coating may be laser machined using a UV-emitting excimer laser. A carbon film outer coating may be laser

machined using a pulsed laser (presumably ablatively) or with a substantially continuous laser (presumably thermally). A photo-resist outer coating may be patterned with a pulsed or continuous laser and processed to remove the outer coating. The techniques hereinafter disclosed may be referred to collectively as "cylindrical lithography" (such cylindrical lithography techniques are also disclosed in U.S. provisional Application No. 60/183,499, cited hereinabove). During laser machining to pattern the mask the optical fiber may be partially rotated about its long axis to produce a partial-ring-like mask pattern 309 on the fiber, extending less than 360° around the circumference of the evanescent waveguide fiber segment. Alternatively, the optical fiber may be fully rotated at a substantially uniform angular velocity while the machining laser is modulated so as to remove the outer fiber coating from only a partial ring portion around the circumference of evanescent waveguide fiber segment 302, leaving mask pattern 309 extending only partially around fiber segment 302. The machining laser may be modulated in any suitable way, including as examples but not limited to: acousto-optic modulation, electro-optic modulation, mechanical shuttering, modulation of the machining laser pump source, photo-elastic modulation, functional equivalents thereof, and/or combinations thereof. The modulation of the machining laser may be timed to and/or synchronized with the rotation of the optical fiber in any suitable manner, including as examples but not limited to: direct mechanical coupling, optical-interrupts, electronic timing circuitry, functional equivalents thereof, and/or combinations thereof.

It should be particularly noted that the cylindrical lithography techniques as disclosed herein may be coupled with any suitable technique for rotational alignment of a polarization-maintaining (PM) optical fiber, so that partial-ring-like mask pattern 309 may be positioned on the surface of evanescent waveguide fiber segment 302 in a predetermined spatial relationship with respect to a polarization axis of the PM fiber. An example of such a rotational alignment technique is the POL technique (Polarization Observation by Lens effect tracing), although other techniques may be equivalently employed. After etching, coupling portion 308 of the surface of evanescent waveguide fiber segment 302 will also be positioned in a similarly predetermined spatial relationship with respect to the polarization axis of the PM fiber. This in turn insures that the polarization state of the propagating optical mode is well-defined and reproducible at the point in the fiber-optic waveguide where the evanescent coupling occurs. Any alignment feedback signal generated by the rotational alignment technique (such as the POL technique)

may also be employed as a timing/synchronization signal for modulation of the machining laser with respect to rotation of the optical fiber, as disclosed in the preceding paragraph.

The rotation of the optical fiber during laser machining should preferably be substantially concentric (thereby substantially minimizing any "orbital" motion of the fiber cross-section about the rotation axis, also referred to as centration error). This may preferably be achieved by using a capillary tube or fiber ferrule to align the fiber for rotation and laser machining. (Hereinafter, use of a capillary tube for fiber alignment as described herein shall be understood to equivalently encompass use of a fiber ferrule or other functionally equivalent structure). A capillary tube should be chosen having an inner diameter closely matching the optical fiber diameter, allowing the optical fiber to rotate within the capillary with little or no orbital motion. For example, the Hermeticoat fiber mentioned hereinabove has a nominal diameter of 125 μm. Capillary tubing is commercially available (0.4 lambda supplied by Drummond Scientific, Inc.) having an inner diameter of 126.4±0.3 μm, making it ideal for concentrically aligning and rotating the fiber during laser machining. This capillary or fiber ferrule alignment technique for substantially concentric rotation of the optical fiber may be employed during any other fabrication step requiring such partial or full rotation of the optical fiber, as set forth hereinbelow. Similar use of a capillary for substantially concentric rotation of an optical fiber during laser processing is described in a publication of Presby et al. (Applied Optics Vol 29, 2692 (1990)), said publication being hereby incorporated by reference in its entirety as if fully set forth herein. While remaining within the scope of inventive concepts disclosed and/or claimed herein, any suitable means may be employed for substantially concentric rotation of the optical fiber during laser machining, including but not limited to a capillary tube, a fiber ferrule, an alignment chuck, an alignment jig, an indexed fiber holder, and so forth. Alternatively, a spindle (air-bearing or otherwise), stepper-motor-driven rotators, servo-motor-driven rotators, encoder, or other rotator may be equivalently employed for rotating the optical fiber during laser machining without a capillary, provided the rotation of the rotator is substantially concentric (i.e., little or no orbital motion of the rotator during rotation) and if the optical fiber can be mounted substantially concentrically with the rotation axis of the rotator.

A preferred method and apparatus are shown generally in Fig. 5 for precisely machining partial rings in a hermetic carbon mask material, wherein the carbon coated fiber may be threaded through a first capillary tube 408 (the alignment capillary). Similar methods and

apparatus may equivalently be employed for other optical fiber outer coatings (polymers, photo-resists, and so forth). A relatively long segment of the carbon coated fiber 402 (as long as several inches or more) may extend from the first end of the capillary 408, and is coupled to a rotation device 400. The rotation device must produce controlled, substantially uniform rotary motion of the fiber with minimal thrust error. (The term "thrust error" refers to any unwanted longitudinal motion that may accompany the desired rotary motion.) The thrust error results in a tilt of the machined partial ring with respect to a plane perpendicular to the fiber axis (an effect which may be used to intentionally produce tilted partial rings, if desired). A prototype system has been successfully constructed using a precision drill press as rotation device 400 (Cameron Micro Drill) with the carbon coated fiber 402 cemented within a second capillary tube 404 and the second capillary tube held within the chuck 406 of the drill press. Without departing from inventive concepts disclosed and/or claimed herein, other devices may be equivalently employed to produce the desired rotary motion, including but not limited to spindles, air-bearing spindles, rotation stages, stepper-motor-driven rotators, servo-motor-driven rotators, encoders, and the like. An air-bearing spindle may be preferred as having the smallest achievable thrust error currently available commercially. For producing partial rings by partial rotation of the optical fiber, such alternative rotation devices may be preferred over the drill press. As the drill press or other rotary device rotates the carbon-coated fiber, the fiber rotates within the first capillary tube 408 with low centration error. As long as both fiber and alignment capillary are substantially uncontaminated, this rotation of the fiber within the capillary will not damage the carbon coating. If desired, it may be possible to drive air or other gas through the capillary around the rotating fiber to serve as an air-bearing. The alignment fiber is substantially rigidly mounted in a standard fiber chuck or other similar device 409, and a relatively short segment of the carbon-coated fiber 402 extends beyond the second end of the alignment capillary 408. A microscope objective 410 (60X in the prototype; others may be used as appropriate) for delivering a laser beam for laser machining may be mounted on a precision 3-axis translator 412 for precise positioning relative to the carbon-coated fiber.

A laser beam 414 from a continuous laser (typically between about 10 mW and about 100 mW average power from a multi-line visible argon ion laser, mainly at about 488 nm and about 514 nm, or a continuous frequency-doubled neodymium-based laser, between about 527 nm and about 532 nm; other laser types, wavelengths, and power levels may be equivalently utilized) is brought to a spot size between about 0.3 μm and about 3 μm, preferably between about 1 μm and

about 2 μm, by the objective 410 onto the surface of the fiber 402 as it rotates, thereby removing the carbon coating from the fiber (presumably by a thermal mechanism). A beamsplitter 416 in the laser beam path allows back-scattered and/or back-reflected laser light from the fiber to be imaged at 418 in order to adjust the focus of the laser beam sufficiently precisely relative to the surface of the fiber. The laser beam need not necessarily be focused at the surface of the fiber (although it could be, if desired). Use of a microscope objective or other high numerical aperture (NA) focusing element is important for several reasons. The highly convergent beam enables the machining of partial rings in the hermetic carbon coating as small as 0.3 to 3 μm wide with sufficiently sharp, well-defined edges, which in turn reduces the roughness of the edges of the coupler portion of the cladding layer surface of the evanescent waveguide fiber segment produced by subsequent etching. A small spot size requires more partial rings to be machined to span a given length of the optical fiber outer coating. A large spot results in an insufficiently well-defined machined edge. Preferably, the largest spot that nevertheless yields a sufficiently well-defined machined edge may be used. A tight focus on the machined surface of the fiber also insures that the laser beam transmitted through the fiber will be sufficiently defocused when it reaches the opposite surface of the fiber so that none of the coating will be removed from the opposing surface, which would degrade the precision of the edges of the machined partial rings and the angular extent of the partial rings. The centration error of the carbon-coated fiber within the capillary tube is typically sub-micron, well within the depth-of-focus of the tightly focused laser beam (typically a few microns). It has also been observed that microscopic defects may occur in the portions of the carbon coating left behind by after laser machining, resulting in unwanted etched spots on the evanescent waveguide fiber segment and adjacent fiber segments and degradation of the performance of the resulting fiber-optic waveguide. It is speculated that hot ejecta from the laser machining may land on adjacent areas (where machining is not desired) and damage the carbon coating. It has been observed that flowing gas (O_2, N_2, and ambient air have been used successfully, although O_2 may be preferable) around the fiber as it is machined seems to substantially eliminate this problem.

It should be noted that a microscope objective may not be required for sufficiently precise machining of partial rings in the carbon coating. In general, if the optical fiber is substantially transparent to the wavelength used for machining the carbon coating (or other fiber outer coating), then the beam must be highly convergent (with an objective or similar optical assembly having an NA greater than about 0.3, preferably around one) so that the transmitted beam is too

large to damage the fiber outer coating on the opposite side of the fiber. However, if the fiber is not transparent to the laser-machining wavelength (157 nm from an F_2 excimer laser, for example, or if the fiber is a hollow fiber filled with material non-transparent at the laser-machining wavelength, or if the fiber is doped to render it non-transparent at the laser-machining wavelength), then damage to the opposite side of the fiber is no longer an issue, and the optical assemblies having longer working distances (i.e., smaller NA) may be employed. This is a general principle that may be applicable to other laser-machining steps set forth hereinbelow. Any laser source suitable for laser machining (known in the art or hereafter developed) may be employed while remaining within the scope of inventive concepts disclosed and/or claimed herein, for any laser machining step disclosed herein.

Alternatively, a suitable partial-ring etch mask may be provided for the evanescent waveguide segment by spatially-selective deposition of an outer fiber coating (i.e., mask material) on the adjacent fiber segment and desired portions of the evanescent waveguide segment, leaving partial (less than 360°) rings of cladding layer surface exposed. Masks may be provided in this way by spatially-selective deposition of an outer fiber coating, which may preferably comprise a metal coating or other suitable coating material. Shadow masking techniques may be employed to achieve spatially-selective deposition of mask material, or the fiber may be positioned within a groove on a substrate prior to deposition of the mask material.

For silica or silicate-based optical fibers, aqueous hydrofluoric acid (HF) is an effective etching agent for spatially-selective removal of material from the desired portions of the length and circumference of the evanescent waveguide fiber segment of the fiber-optic waveguide after providing a suitable mask. The amount of material removed can be precisely controlled by controlling the etching time, etchant concentration and/or pH, and/or temperature. The etched surfaces are substantially smooth and substantially free of irregularities, thereby minimizing optical scatter from the etched surfaces of the fiber-optic waveguide. The concentration of HF used to etch the optical fiber may be between about 5% and about 50% HF buffered with NH_4F, should preferably be between about 7% and about 8% HF and between about 30% and about 40% NH_4F, and most preferably about 7.2% HF and 36% NH_4F. The most preferred concentration yields an etch rate of about 80 nm/min, and is available commercially (Transene Company, Inc.). Another suitable HF concentration is 1 part 40% HF(aq) combined with 10 parts 40% NH_4F(aq), as disclosed in the publication of Eisenstein et al. (Applied Optics **21** 3470

(1981), said publication being incorporated by reference in its entirety as if fully set forth herein. Any of these disclosed concentrations may be employed during any other fabrication step requiring an HF etch, as set forth hereinbelow. While remaining within the scope of inventive concepts disclosed and/or claimed herein, any suitable wet or chemical etching agent (either known in the art or hereafter developed) may be used to reduce the diameter of the adjacent fiber segments or other portions of the fiber. Alternatively, dry or reactive ion etching procedures, employing suitable etch masks (metal masks or polymer masks, for example), may be used to reduce the diameter of the adjacent fiber segments or other portions of the fiber. After etching, the mask may be removed by any of a variety of methods, including but not limited to non-spatially-selective laser machining, chemical/solvent removal, thermal removal (i.e., burning), exposure to an electrical discharge, plasma ashing, ion sputtering, and other suitable methods for removing the mask (known in the art or hereafter developed).

It should be noted that as the etching process proceeds radially inward from the laser-machined partial rings (i.e., the "un-masked" portion of the surface of the evanescent waveguide fiber segment 302), transverse edges of the evanescent waveguide fiber segment become exposed to the etchant and come under attack. The resulting coupling portion 308 of the cladding layer surface of the evanescent waveguide fiber segment 302 therefore often acquires a saddle-like shape, having a concave longitudinal-sectional shape (Fig. 3E) near at least a portion of the core 304 of the evanescent waveguide fiber segment 302 and a convex transverse-sectional profile (Fig. 3D) near at least a portion of the core 304 of the evanescent waveguide fiber segment 302. The precise shapes and radii-of-curvature of these (not necessarily circularly arcuate) sectional profiles may be controlled by the size (width and circumferential extent) and/or shape of the outer fiber coating (mask material 309/319) removed during the mask-providing step, and by controlling the etching time, etchant concentration and/or pH, and/or temperature. For example, a wider partial ring of removed mask material would result in a more shallow longitudinal section (larger concave radius of curvature). A partial ring of removed mask material having a larger circumferential extent would yield a sharper transverse section (smaller convex radius of curvature). For a given combination of optical fiber type/material and etchant, some experimentation is required to correlate mask size/shape, etching time and/or conditions, and the details of the shape of the resulting coupling portion 308 of the surface of the cladding layer 306 of the evanescent waveguide fiber segment 302. Once these correlations are

established, they may be used to reliably and reproducibly produce fiber-optic waveguides according to the present invention.

By reducing the circumferential extent of the "unmasked" portion of the surface of evanescent waveguide fiber segment 302, the convex transverse sectional profile of coupling portion 308 may be made less sharply curved, or even substantially flat (Figs. 6A and 6B). This may offer the advantages of D-shaped fiber as disclosed hereinabove, without the attendant difficulties of splicing D-shaped optical fiber to standard, substantially circular-cross-sectioned single-mode optical fiber (PM or otherwise). Further reducing the circumferential extent of the "unmasked" portion of the evanescent waveguide fiber segment (for example resulting in essentially a longitudinal slit-like "unmasked" portion of the surface of evanescent waveguide fiber segment 302) may result (after etching) in coupling portion 308 of the cladding layer surface acquiring a scooped, or pit-like, shape having concave profiles in both longitudinal and transverse sections (Figs. 7A and 7B).

Another method for tailoring the shape of coupling portion 308 comprises machining of multiple partial rings on evanescent waveguide fiber segment 302, leaving an intervening ring of outer fiber coating material between each pair of adjacent partial rings (Fig. 17). The intervening rings are sufficiently narrow so that upon etching of the cladding layer 306, the multiple etched surfaces (each resulting from one of the machined partial rings) coalesce into a single coupling portion 308 of evanescent waveguide fiber segment 302. Coupling portion 308 may initially be rough, but further etching after the partial rings coalesce results in a substantially smooth cladding layer surface. By tailoring the number, widths, spacings, and circumferential extents of each of the multiple partial rings (independently; they need not all be the same), virtually any desired shape for coupling portion 308 may be achieved. For a given combination of optical fiber type/material and etchant, some experimentation is required to correlate the number, widths, spacings, and circumferential extents of each of the multiple partial rings, etching time and/or conditions, and the details of the shape of the resulting coupling portion 308 of the surface of the cladding layer 306 of the evanescent waveguide fiber segment 302. Once these correlations are established, they may be used to reliably and reproducibly produce fiber-optic waveguides according to the present invention.

The fiber-optic waveguide thus fabricated is more robust than a fiber taper. The cladding layer remaining on the evanescent waveguide fiber segment transversely opposite the coupling

portion of the cladding layer surface may be several tens of microns thick, in contrast to the 1-5 μm total thickness of a typical fiber taper. The overall length of the coupling portion may be as small as about a hundred microns long, whereas a typical tapered segment of an optical fiber taper may be substantially longer, and therefore less mechanically stable, rigid, and/or robust. The fiber-optic waveguide according to the present invention is therefore a substantially sturdier structure, able to withstand manipulation without excessive breakage and to maintain alignment once secured to an alignment structure. Furthermore, fiber tapers are often capable of supporting many different propagating optical modes, complicating the use of such fiber tapers for coupling to single whispering-gallery optical modes of a WGM optical resonator. A fiber-optic waveguide fabricated according to the present invention, however, typically retains the single-mode characteristics of the fiber from which it was fabricated. Fiber-optic waveguides according to the present invention may be fabricated from polarization-maintaining (PM) optical fiber, thereby enabling polarization-specific propagation of an optical mode through the waveguide as well as polarization-specific evanescent coupling to the WGM optical resonator.

A saddle-like shape of the coupling surface of the evanescent waveguide fiber segment may be tailored to facilitate subsequent use of the fiber-optic waveguide for evanescent optical coupling to a whispering-gallery-mode optical resonator, as illustrated in Figs. 8A and 8B. For example, such WGM resonators can take the form of fiber-rings (as disclosed in provisional Application No. 60/183,499, cited hereinabove), micro-spheres, micro-disks (including structures such as a "thumbtack" fabricated on a substrate, wafer, or chip; described in earlier-cited publication P7 and disclosed in U.S. Patent No. 5,343,490, said patent being hereby incorporated by reference as if fully set forth herein), and/or micro-rings (including structures such as a "ring mesa" fabricated on a substrate, wafer, or chip) which must be brought into substantial tangential engagement with the coupling portion of the surface of the cladding layer of the evanescent waveguide fiber segment. The concave radius of curvature of the longitudinal-sectional shape of saddle-shaped coupling portion 308 of the cladding layer surface should preferably be at least about as large as the radius of the WGM optical resonator 602, thereby enabling reliable, reproducible, and stable optical coupling between a whispering-gallery optical mode of the resonator 602 and the propagating optical mode in the evanescent waveguide fiber segment 302. The concave radius of curvature of the longitudinal-sectional shape may also determine the degree of evanescent optical coupling between the propagating optical mode in the fiber-optic waveguide 302 and the whispering-gallery optical mode of the WGM optical

resonator 602. Reliable, reproducible, and stable evanescent optical coupling between the fiber-optic waveguide and a WGM resonator may be further enabled by the transverse-sectional shape of the coupling portion 308 of the cladding layer 306. In particular, for a fiber-ring WGM optical resonator as disclosed in Application No. 60/183,499 (cited and incorporated by reference hereinabove), a substantially flat or convex transverse sectional profile for coupling portion 308 is necessary (Figs. 8A and 8B). For a micro-sphere WGM optical resonator, however, a concave transverse sectional profile for coupling portion 308 may be more suitable for enabling reliable, stable, and reproducible evanescent optical coupling. For a "thumbtack" micro-disk WGM resonator fabricated on a substrate, a longitudinally elongated coupling portion 308 having both transverse and longitudinal sectional profiles convex may be most suitable for enabling reliable, stable, and reproducible evanescent optical coupling (Figs. 9A and 9B). It should be noted that whatever methods/techniques may be employed for asymmetric removal of cladding layer material from the evanescent waveguide fiber segment (disclosed herein or otherwise), the shape of the resulting coupling portion of the cladding surface may be controlled in the manner and for the purposes as stated hereinabove.

In order to achieve evanescent optical coupling between the fiber-optic waveguide 300 and a WGM optical resonator 602, at least a portion of the core 304 of the evanescent waveguide fiber segment 302 must be sufficiently near the coupling potion 308 of the surface of the cladding layer 306 thereof, thereby enabling an evanescent portion of the propagating optical mode to extend transversely beyond the coupling portion 308 of the cladding layer surface. The thickness of cladding layer material remaining between the core 304 and the coupling portion 308 of the cladding layer surface may preferably be between about 0 μm (exposed core) and about 10 μm, although the thickness may be as large as about 30 μm. Since the doped core of many optical fibers etches more slowly than the cladding layer, the coupling portion 308 of the cladding layer surface may be etched away leaving a protruding "ridge" waveguide comprising the exposed core 304, as shown in Figs. 10A and 10B. As with the shape of the coupling portion 308 of the cladding layer surface, experimentation may be required to establish correlations between mask size/shape, etching time and/or conditions, and the resulting thickness of cladding layer material 306 remaining over the core 304 for a given combination of optical fiber type/material and etchant. Once these correlations are established, they may be used to reliably and reproducibly produce fiber-optic waveguides according to the present invention.

Another technique for controlling the removal of cladding layer material comprises the step of monitoring the optical loss of the fiber-optic waveguide 300 as cladding material 306 is removed. As the coupling portion 308 of the cladding layer surface moves closer to the core 304 of the evanescent waveguide fiber segment 302, optical loss from the cladding layer surface increases, thereby decreasing the throughput of the fiber-optic waveguide 300. By terminating the etching step in response to the optical loss reaching some pre-determined level, the coupling portion 308 of the cladding layer surface may reproducibly be brought to within a specified distance of the core 304. Target levels for the optical loss of the fiber-optic waveguide range between about 0.1 dB and about 30 dB, preferably between about 0.1 dB and about 10 dB, and most preferably between about 0.1 dB and about 3 dB. Experimentation may be required to establish correlations between measured optical loss and the corresponding thickness of cladding layer material remaining over the core. The ranges for the pre-determined loss level may be measured with the fiber-optic waveguide is immersed in the etchant, or removed from the etchant (with or without being cleaned and/or dried).

In order to more readily achieve and maintain reliable, reproducible, and stable optical coupling between a WGM optical resonator 602 (particularly a fiber-ring WGM optical resonator as disclosed in provisional Application No. 60/183,499, cited hereinabove) and a fiber-optic-waveguide 300 according to the present invention, the fiber-optic waveguide 300 may be fabricated from polarization-maintaining (PM) optical fiber. Panda-type PM optical fiber (Fig. 1) may preferably be used to fabricate a fiber-optic waveguide using mask-and-etch methods according to the present invention. The stressor elements of the PM fiber, like the core, generally etch at a slower rate than the surrounding cladding layer material. After masking and etching according to the techniques disclosed herein, longitudinally extending passive alignment structures 305 result which extend transversely from the coupling portion 308 of the cladding layer surface of the evanescent waveguide fiber segment 302 (Fig. 11A). These passive alignment structures 305 are positioned in a predetermined spatial relationship with respect to the polarization axis of the PM optical-fiber as disclosed hereinabove, and may therefore be particularly well-suited for achieving and maintaining reliable, reproducible, stable, and polarization-specific optical coupling between the fiber-optic waveguide 300 and a fiber-ring WGM optical resonator 602, as shown in Figs. 11B and 11C and disclosed in provisional Application No. 60/183,499 (cited hereinabove). The fiber-ring WGM resonator 602 may be provided with suitable mating mechanical indexing structures 606 on adjacent fiber segments

604 for further facilitating reliable, reproducible, and stable optical coupling (Fig. 11B). Contact between alignment structures 305 and fiber-ring 602 may affect the performance of the embodiment of Fig. 11C.

Without departing from inventive concepts disclosed and/or claimed herein, any suitable methods or techniques (currently extant or hereafter developed) may be employed for asymmetric removal of cladding layer material from the evanescent waveguide fiber segment. Such removal of cladding material may be performed subject to constraints, requirements, and controls as described elsewhere herein. Such methods or techniques may include but are not limited to: masking/etching; wet etching; chemical etching; plasma etching; dry etching; ion beam lithography; direct laser machining of cladding layer material; mechanical machining, polishing, lapping, and/or grinding of cladding material; ablative techniques; functional equivalents thereof; and/or combinations thereof.

In a resonant optical power control device according to the present invention, a WGM optical resonator is coupled to a fiber-optic waveguide according to the present invention. A propagating optical mode (equivalently, an optical carrier wave) to be controlled propagates through the fiber-optic waveguide where it may be controlled, modulated, and/or routed, either passively or by application of control signals to the control device. The fiber-optic waveguide is adapted (as disclosed hereinabove) to enable evanescent optical coupling between the propagating optical mode of the fiber-optic waveguide and a resonant whispering-gallery optical mode of the WGM optical resonator or other optical resonator and/or waveguide, thereby enabling controlled modulation and/or routing of the propagating optical mode of the fiber-optic waveguide. Such optical power control devices and control, modulation, and/or routing techniques are described in detail in: U.S. provisional Application No. 60/111,484; U.S. Application No. 09/454,719; U.S. provisional Application No. 60/108,358; U.S. Application No. 09/440,311; and U.S. provisional Application No. 60/183,499. Each of these applications has been incorporated herein by reference.

In order to achieve and maintain reliable, reproducible, and stable optical coupling between a fiber-optic waveguide and a WGM resonator during and after manufacture of a resonant optical power control device according to the present invention, an alignment device may be employed (Figs. 12, 13A, 13B, 14A, 14B, 16A, 16B, and 16C). Such an alignment device may comprise a first alignment substrate 502 having a waveguide-alignment groove 506

and a resonator-alignment groove 504 thereon. A method for fabricating a resonant optical power control device according to the present invention comprises the steps of: 1) positioning and securing a fiber-optic waveguide 300 within the waveguide-alignment groove 506; and 2) positioning and securing the WGM optical resonator (for example a fiber-ring WGM resonator 602 as disclosed in provisional Application No. 60/183,499, a micro-sphere, or of some other functionally equivalent configuration as enumerated earlier herein) within the resonator-alignment groove 504. The waveguide-alignment groove 506 and resonator-alignment groove 504 may be positioned on the alignment substrate 502 so that when positioned and secured therein, the fiber-optic waveguide 300 and the fiber-ring WGM resonator 602 are in substantial tangential engagement (typically mechanical contact between the coupling portion 308 of the cladding layer surface of the evanescent waveguide fiber segment 302 and the circumference of the resonator 602; see below and Figs. 8A, 8B, 13A, 13B, 14A, and 14B), thereby optically coupling the WGM resonator 602 to the fiber-optic waveguide 300. Optical coupling between the WGM resonator 602 and the fiber-optic waveguide 300 may be achieved as long as at least part of the evanescent wave portions of each of the whispering-gallery optical mode of the resonator and the propagating optical mode of the fiber are spatially overlapped. The degree of overlap and the degree of phase matching determines the degree of optical coupling between the resonator and the fiber. Actual mechanical contact is not required, only that the resonator and waveguide be sufficiently close to permit the overlap. However, in a preferred embodiment of an optical power control device according to the present invention, optical coupling between the resonator and the waveguide is most reproducibly, reliably, and stably achieved by positioning and securing the WGM resonator 602 and the fiber-optic waveguide 300 in mechanical contact with one another within each respective alignment groove. Figs. 16A, 16B, and 16C show a similar configuration of a fiber-optic waveguide 300 and a WGM micro-sphere resonator 620 connected to a tapered end 632 of an optical fiber 624.

As shown in Fig. 12, the resonator-alignment groove and the waveguide-alignment groove may preferably be substantially perpendicular, so that the waveguide 300 and WGM fiber-ring resonator 602 may be substantially co-planar. Similarly, substantially perpendicular alignment grooves insure that a WGM micro-sphere resonator would be aligned with its symmetry axis substantially perpendicular to fiber-optic waveguide 300 (Figs. 16A and 16B; it should be noted the such "micro-spheres" are typically slightly oblate, with a symmetry axis substantially coinciding with the tapered fiber end). The alignment grooves may have

substantially constant width and depth profiles along their respective lengths, or alternatively may have tailored width and/or depth profiles. The cross-sectional shape of the alignment grooves may preferably be substantially rectangular (in fact generally slightly trapezoidal due to laser machining or other etch processes typically employed), but may alternatively have any suitable cross-sectional shape for positioning and securing the WGM resonator and the fiber-optic waveguide. The depths of the resonator-alignment groove and waveguide-alignment groove are preferably chosen so that when positioned and secured therein, the waveguide and WGM resonator are in direct contact and therefore optically coupled in a reproducible, reliable, and stable manner (Figs. 13A, 13B, 14A, 14B, 16A, and 16B). The depths chosen depend on the mechanical configurations of the WGM resonator and the fiber-optic waveguide, as may be readily determined for a particular configuration by one skilled in the art. Either the waveguide-alignment groove or the resonator-alignment groove may be the deeper groove, and typically the component (waveguide or resonator) corresponding to the deeper groove is positioned and secured in its respective groove first, and the other component positioned and secured after the first, although this need not always be the case. If multiple WGM resonators are to be coupled to a single fiber-optic waveguide through multiple evanescent coupling surfaces, the multiple WGM resonators may be positioned in alternating positions above and below the fiber-optic waveguide, thereby enhancing the overall mechanical stability of the assembly (not shown). Any of a variety of functionally equivalent methods may be employed for securing the fiber-optic waveguide and/or the WGM resonator within the respective alignment groove, including but not limited to: application of adhesives, epoxies, resins, polymers, solders, and the like; welding or fusing; and providing a mechanical retainer for retaining the fiber-optic waveguide and/or WGM resonator within the respective alignment groove, such as a clamp, clip, fastener, plate, or other like device. In an alternative embodiment of an optical power control device, the fiber-optic waveguide may be fused or welded (with a CO_2 laser, for example) to the circumference of a WGM resonator to insure stable, reliable, and reproducible optical coupling. Once the fiber-optic waveguide and WGM resonator have each been positioned and secured within the respective alignment groove, the alignment device may be sealed (preferably hermetically sealed) to isolate the fiber and resonator from the use environment of the optical power control device. This is important for a number of reasons. First, the optical coupling relies on the propagation of evanescent optical waves from free surfaces of the fiber-optic waveguide and WGM resonator. Any contamination of these free surfaces may drastically alter

the optical properties of the waveguide and/or resonator and/or optical coupling thereof, thereby altering the performance of the optical power control device. Similarly, any movement of the fiber-optic waveguide relative to the WGM resonator may also alter the optical coupling and performance of the control device. The alignment device may comprise a cover, second substrate, or other functionally equivalent component 508 that may be positioned over the alignment grooves and sealed into place (using adhesives, epoxies, resins, polymers, solders, and/or the like; or using welding or fusion), leaving the two ends of the fiber-optic waveguide exposed for connecting to an optical power transmission system (Figs. 13A, 14A, and 16A).

In a preferred embodiment of a optical power control device according to the present invention, a WGM resonator is employed having been fabricated from an optical fiber as disclosed in provisional Application No. 60/183,499. Such a WGM resonator fabricated from an optical fiber and comprising a resonator fiber segment 602 and adjacent fiber segments 604 may be particularly well-suited for use in the optical power control device fabrication methods described herein. The adjacent fiber segments 604 may serve to reproducibly, reliably, and stably position the WGM resonator 602 within the resonator-alignment groove 504, particularly in directions substantially orthogonal to the longitudinal axis of the resonator fiber segment 602 and adjacent fiber segments 604. Proper longitudinal positioning is required so that the fiber-optic waveguide 300 tangentially engages the resonator fiber segment 602 and not an adjacent fiber segment 604. This may be most simply accomplished by providing a blind resonator-alignment groove 504, truncating an adjacent fiber segment 604 at an appropriate length, and positioning the WGM resonator 602 in resonator-alignment groove 504 so that the truncated end of adjacent fiber segment 604 butts up against the blind end of resonator-alignment groove 504. If the truncated end is angle polished and the blind groove end is angled, rotation of the fiber may serve to adjust the longitudinal position of the WGM resonator within resonator-alignment groove 504. Alternatively, alignment structures provided on the adjacent fiber segments 604 may serve to properly longitudinally position the WGM resonator 602 within the resonator-alignment groove 504. Preferred alignment structures that may be provided on one or more of the adjacent fiber segments 604 may comprise circumferential grooves and/or circumferential annular flanges for engaging corresponding complimentary alignment structures (flanges and/or grooves, respectively) that may be provided in the resonator-alignment groove 504 of the alignment substrate 502. Such alignment structures are more fully disclosed in provisional Application No. 60/183,499, cited hereinabove. Other suitable alignment structures may be

employed while remaining within the scope of inventive concepts disclosed and/or claimed herein. The fiber-optic waveguide 300 may be precisely transversely positioned by virtue of waveguide-alignment groove 506, while the concave longitudinal-sectional shape of the coupling portion 308 of the cladding layer surface of the evanescent waveguide fiber segment 302 may preferably serve to longitudinally position the fiber-optic waveguide 300 within the waveguide-alignment groove 506 with respect to the WGM resonator 602. Alternatively, fiber-optic waveguide 300 may be provided with alignment structures (grooves, flanges, or the like) on adjacent fiber segments 312 in a manner analogous to that disclosed for the WGM resonator 602 and adjacent fiber segments 604, and corresponding complimentary structures may be provided in waveguide-alignment groove 506.

In an alternative embodiment of a optical power control device according to the present invention, a WGM micro-sphere resonator is employed having been fabricated from an optical fiber as disclosed in earlier-cited applications A1 through A4. Such a WGM micro-sphere resonator fabricated from an optical fiber and comprising a micro-sphere resonator 620 connected to a tapered section 622 of an optical fiber 624 may be employed in the optical power control device fabrication methods described herein. The optical fiber 624 may serve to reproducibly, reliably, and stably position the WGM micro-sphere resonator 620 within the resonator-alignment groove 504, particularly in directions substantially orthogonal to the symmetry axis of the micro-sphere resonator 620. Proper longitudinal positioning is required so that the fiber-optic waveguide 300 tangentially engages the micro-sphere resonator 620. This may be most simply accomplished by providing a blind resonator-alignment groove 504, truncating the optical fiber 624 at an appropriate length, and positioning the WGM micro-sphere resonator 620 in resonator-alignment groove 504 so that the truncated end of the optical fiber 624 butts up against the blind end of resonator-alignment groove 504. If the truncated end is angle polished and the blind groove end is angled, rotation of the fiber may serve to adjust the longitudinal position of the WGM resonator within resonator-alignment groove 504. Alternatively, alignment structures provided on the optical fiber 624 may serve to properly longitudinally position the WGM micro-sphere resonator 620 within the resonator-alignment groove 504. Preferred alignment structures that may be provided on the optical fiber 624 may comprise circumferential grooves and/or circumferential annular flanges for engaging corresponding complimentary alignment structures (flanges and/or grooves, respectively) that may be provided in the resonator-alignment groove 504 of the alignment substrate 502. Such

alignment structures are more fully disclosed in provisional Application No. 60/183,499, cited hereinabove. Other suitable alignment structures may be employed while remaining within the scope of inventive concepts disclosed and/or claimed herein. The fiber-optic waveguide 300 may be precisely transversely positioned by virtue of waveguide-alignment groove 506, while the concave longitudinal-sectional shape of the coupling portion 308 of the cladding layer surface of the evanescent waveguide fiber segment 302 may preferably serve to longitudinally position the fiber-optic waveguide 300 within the waveguide-alignment groove 506 with respect to the WGM micro-sphere resonator 620. Alternatively, fiber-optic waveguide 300 may be provided with alignment structures (grooves, flanges, or the like) on adjacent fiber segments 312 in a manner analogous to that disclosed for the WGM resonator 602 and adjacent fiber segments 604 or optical fiber 624, and corresponding complimentary structures may be provided in waveguide-alignment groove 506.

A major portion of the cost associated with manufacture of optical power control devices arises from the labor-intensive steps involved in properly aligning the components of the device. Often active alignment techniques are required wherein some measure of device performance (examples include insertion loss, modulation depth, bandwidth, and so forth) is monitored and optimized with respect to alignment of components of the device. Such active alignment steps are reduced or substantially eliminated from fabrication of a resonant optical power control device according to the present invention. For example, appropriate depths chosen for the resonator-alignment groove and the waveguide-alignment groove, and circumferential grooves and/or annular flanges provided on an adjacent fiber segment or connected optical fiber and appropriately positioned mating structures in the resonator-alignment groove for engaging the grooves/flanges, both serve to enable positioning of the WGM resonator in substantial tangential engagement (in mechanical contact, for example) with the fiber-optic waveguide when each is positioned within the respective alignment groove, without any need for active monitoring of device properties during assembly and/or alignment. Such passive alignment techniques substantially reduce manufacturing time and cost, and substantially enhance reliability and consistency of the manufactured devices.

Whispering-gallery-mode optical (WGM) resonators and methods for fabrication thereof have been described in earlier-cited applications A1 through A5 wherein the WGM resonator (fiber-ring, micro-sphere, or other functionally equivalent resonator structure) may be provided

with a modulator for enabling controlled modulation of optical properties of the WGM resonator. The modulator may be provided in a variety of ways, including but not limited to: in a WGM resonator fabricated by providing material on the circumference of a resonator fiber segment, the material provided may enable modification of optical properties of the WGM resonator; in a WGM resonator fabricated by spatially-selective doping of a resonator fiber segment, the doped material may enable modification of optical properties of the WGM resonator; a modulator material may be provided on at least a portion of the circumference of the WGM resonator and therefore be encompassed by an evanescent portion of the WGM optical wave extending radially from the resonator fiber segment; an adjacent fiber segment may be truncated sufficiently close to the resonator fiber segment so that at least a portion of the resulting fiber end face is encompassed by a evanescent wave portion of the WGM optical wave extending longitudinally from the resonator fiber segment, and a modulator material may be provided on the portion of the fiber end face thus encompassed; combinations thereof; and/or functional equivalents thereof. The modulator material (including deposited, bonded, attached, and/or doped material) may include but is not limited to: an electro-optic material; an electro-absorptive material; a non-linear optical material; a semi-conductor material (including hetero-structures such as quantum wells); an optical gain medium (a laser material, for example); a piezo-electric material; combinations thereof; and/or functional equivalents thereof. The modulator may enable controlled modulation of one or more optical properties of the WGM resonator, including but not limited to: optical gain and/or loss; optical coupling to the WGM resonator; a resonant frequency of the WGM resonator; combinations thereof; and/or functional equivalents thereof.

For each of the various modulator structures, methods, and materials recited hereinabove for a WGM resonator, some sort of control signal must be applied to the modulator. A modulator control element may therefore be provided on the alignment device for providing such signals to a modulator of a WGM resonator. Such signals may comprise an electronic control signal, an optical control signal, a mechanical control signal, and/or other control signal, and the modulator control element may comprise means for applying such control signals to the modulator. Examples of such means may include, but are not limited to: electrical conductors, wires, cables, electrodes, electrical contacts, ohmic contacts, wireless transmitters and/or receivers, semiconductors, semiconductor hetero-structures (including quantum wells), diodes, triodes, transistors, field-effect transistors (FET's), CMOS devices, integrated circuits, ASIC's, digital circuits, analog circuits, optical fibers, lenses, micro-lenses, mirrors, prisms, integrated

optics, adaptive optics, light sources, laser sources, laser diodes, light-emitting diodes (LED's), photo-voltaic devices, photo-conductive devices, piezo-electric devices, electrostrictive devices, actuators, translators, rotators, linear and/or rotary stepper motors, linear and/or rotary servo systems, combinations thereof, and/or functional equivalents thereof. Several specific illustrative examples follow. An electronic and/or optical control signal may be applied to an optically thin semiconductor quantum well material provided on a fiber end face, for example, thereby altering the optical loss of the WGM resonator. An optical and/or electronic signal may be applied to an electro-optic material deposited on the resonator fiber segment, thereby altering the WGM resonator refractive index and therefore also altering a resonant frequency of the WGM resonator. A mechanical control signal may be applied via a piezo-electric, electro-static, or micro-electro-mechanical (MEM) control element to move a fiber-optic waveguide into or out of mechanical contact with the circumference of the WGM resonator, thereby altering the optical coupling between the WGM resonator and the fiber-optic waveguide. A mechanical control signal may be applied via a piezo-electric, electro-static, or micro-electro-mechanical (MEM) control element to move a resonator loss element into or out of mechanical contact with the circumference of the WGM resonator, thereby altering the optical loss of the WGM resonator. The foregoing are exemplary only, and many other modulation schemes may be devised for application of control signals for modulating of WGM resonator optical properties while remaining within the scope of inventive concepts disclosed and/or claimed herein. A portion of the modulator control element may reside on and/or within the alignment device, and access to the control element may be provided enabling control of the modulator after hermetic sealing of the alignment device.

The application of a control signal to a modulator of a WGM resonator via a modulator control element enables controlled modulation of the optical power transmitted through the fiber-optic waveguide of the optical power control device. This may be accomplished in a variety of ways, depending on the nature of the modulator employed, and several specific examples follow. Modulating the optical loss of the WGM resonator between essentially zero loss and the so-called critical-coupling loss (wherein the WGM loss roughly equals the coupling between the transmission fiber and the WGM resonator) enables modulation of an optical wave that is resonant with a whispering-gallery mode of the WGM resonator between about 0% (substantially unattenuated transmission) and about 100% (substantially blocked transmission). A similar result may be obtained by keeping the WGM optical loss constant while modulating the optical

coupling between the fiber-optic waveguide and the WGM resonator. Alternatively, modulating a resonant frequency of a WGM having optical loss substantially equal to the critical-coupling loss may enable similar modulation of an optical wave as the WGM resonant frequency is moved out of and brought into resonance with the optical wave. The foregoing are exemplary only, and many other fiber-optic waveguide modulation schemes may be devised by suitable modulation of WGM resonator optical properties while remaining within the scope of inventive concepts disclosed and/or claimed herein.

In addition to the fiber-optic waveguide and the WGM resonator (and possibly including a modulator and a modulator control element), an optical power control device according to the present invention may further comprise a secondary optical assembly positioned on the alignment device substantially tangentially engaged with the WGM resonator fiber segment, as disclosed in applications A1 through A5, cited hereinabove. The secondary optical assembly may therefore be optically coupled to the WGM resonator, and coupled to the fiber-optic waveguide therethrough. The modulator (if present) may be employed to actively modulate the optical coupling between the secondary optical assembly and the fiber-optic waveguide through modulation of optical properties of the WGM resonator and/or coupling between the WGM resonator and the fiber-optic waveguide and/or the secondary optical assembly in a manner similar to that described hereinabove. Alternatively, the optical coupling/interactions between the fiber-optic waveguide, WGM optical resonator, and secondary optical assembly may be passive. The secondary optical assembly may comprise a second fiber-optic waveguide (thereby enabling controlled switching or passive routing of an optical wave propagating along the first fiber-optic waveguide to the second fiber-optic waveguide; Figs. 15A and 15B), a waveguide of another type, or the secondary optical assembly may comprise a second WGM optical resonator (thereby enabling, for example, controlled modification/modulation of the overall properties of the optical power control device, particularly the wavelength dependence of the control device). The secondary optical assembly may be positioned on and secured to the alignment device on the same alignment substrate as the first fiber-optic waveguide and first WGM resonator, or the alignment device may comprise a second alignment substrate with the secondary optical assembly positioned and secured thereto. Such a secondary optical assembly and/or second alignment substrate may be suitably indexed or provided with mating alignment structure(s) to enable reproducible, reliable, and stable alignment of the secondary optical assembly with the first WGM resonator when the optical power control device is assembled. The alignment device,

including the first fiber-optic waveguide, the first WGM optical resonator, and the secondary optical assembly, may be sealed (preferably hermetically sealed) after assembly, as disclosed hereinabove. A cover, the second alignment substrate, or another functionally equivalent component may be positioned over the alignment grooves and sealed into place (using welding, fusion, adhesives, epoxies, resins, polymers, solders, and/or the like), leaving only the two ends of the fiber-optic waveguide exposed for connecting to an optical power transmission system. A portion of the modulator control element (if present) may reside on and/or within the assembled alignment device, and access to the control element may be provided enabling control of the modulator after hermetic sealing of the alignment device. Such access may comprise feed-through connectors, access ports, windows, embedded conductors and/or optical fibers, and the like for transmitting optical, electronic, or mechanical control signals.

A specific example of an optical power control device according to the present invention suitable for routing optical signals is shown in Figs. 15A and 15B. Two fiber-optical waveguides 300 and 800 are shown coupled to the same WGM optical resonator 602. A propagating optical mode in fiber-optic waveguide 300 may be routed into fiber-optic waveguide 800 by evanescent optical coupling of each waveguide to WGM resonator 602, depending on the wavelength of the propagating optical mode and the resonance wavelength(s) of WGM resonator 602. Routing of optical signals in this way may be passive, the wavelength-dependence of the routing relying on the optical properties of WGM resonator 602. Alternatively, routing of optical signals using a device as shown in Figs. 15A and 15B may be actively controlled, by active control of optical coupling of waveguide 300 and/or waveguide 800 to resonator 602, and/or active control of properties of resonator 602. Waveguides 300 and 800 and resonator 602 may be reproducibly, reliably, and stably positioned using a suitable alignment device comprising first and second alignment substrates 502 and 510 and may be hermetically sealed within as disclosed herein. The one or both ends of waveguides 300 and 800 may extend beyond the alignment device (Fig. 15A) for connecting to an optical power transmission system.

Instead of providing a modulator on the WGM resonator, a modulator (if present) may alternatively comprise a separate modulator optical assembly. Modulation of the optical properties of the modulator optical assembly (rather than modulation of the optical properties of the WGM resonator) serves to modulate the optical power transmitted through the fiber-optic waveguide. The modulator optical assembly may preferably be positioned in substantial

tangential engagement with the WGM resonator fiber segment (and therefore optically coupled to the WGM resonator) and secured to the alignment device. The modulator optical assembly may comprise any of a wide variety of devices, including but not limited to: an optical gain and/or loss modulator, a non-linear optical device, an electro-optic device, an electro-absorptive device, a semiconductor device (including semiconductor heterostructures, such as quantum wells), a second fiber-optic or other evanescent waveguide, a second WGM resonator (which may further comprise a modulator, as described above), composite structures comprising multi-layer dielectric stacks incorporating an electro-optic layer, combinations thereof, and/or functional equivalents thereof. The optical properties of the modulator optical assembly may be controlled and/or modulated to modulate the transmission of optical power through the fiber-optic waveguide as described hereinabove for a modulator provided on the WGM resonator. A control signal (electronic, optical, mechanical, or other) may be applied to the modulator optical assembly as described hereinabove, and the alignment device may comprise a component (a modulator control element) for delivering such control signals to the modulator optical assembly, as described hereinabove. The application of a control signal to the modulator optical assembly via a modulator control element enables controlled modulation of the optical power transmitted through the fiber-optic waveguide of the optical power control device and may be accomplished in a variety of ways, depending on the nature of the modulator employed. Several specific examples follow. Modulating the optical loss of an optical loss modulator optically coupled to the WGM resonator between essentially zero loss and the so-called critical-coupling loss (wherein the loss roughly equals the coupling between the transmission fiber and the WGM resonator) enables modulation of a propagating optical mode that is resonant with a whispering-gallery mode of the WGM resonator between about 0% (substantially unattenuated transmission) and about 100% (substantially blocked transmission). A similar result may be obtained by keeping the modulator optical loss constant while modulating the optical coupling between the modulator optical assembly and the WGM resonator. Alternatively, modulating a resonant frequency of a second WGM (part of the modulator optical assembly) may enable similar modulation of a propagating optical mode as the second WGM resonant frequency is moved out of and brought into resonance with the propagating optical mode. The foregoing are exemplary only, and many other fiber-optic waveguide modulation schemes may be devised by suitable modulation of WGM resonator optical properties while remaining within the scope of inventive concepts disclosed and/or claimed herein.

The modulator optical assembly may be positioned on and secured to the alignment device on the same alignment substrate as the fiber-optic waveguide and WGM resonator, or the alignment device may comprise a second alignment substrate with the modulator optical assembly positioned and secured thereto. The modulator optical assembly and/or second alignment substrate may be suitably indexed or provided with mating alignment structure(s) to enable reproducible, reliable, and stable alignment of the modulator optical assembly with the WGM resonator when the optical power control device is assembled. The alignment device, including the fiber-optic waveguide, the WGM optical resonator, and the modulator optical assembly, may be sealed (preferably hermetically sealed) after assembly, as disclosed hereinabove. A cover, the second alignment substrate, or another functionally equivalent component may be positioned over the alignment grooves and sealed into place (using adhesives, epoxies, resins, polymers, solders, and/or the like), leaving only the two ends of the fiber-optic waveguide exposed for connecting to an optical power transmission system. A portion of the modulator control element may reside on and/or within the assembled alignment device, and access to the control element may be provided enabling control of the modulator after hermetic sealing of the alignment device. Such access may comprise feed-through connectors, access ports, embedded conductors and/or optical fibers, and the like for transmitting optical, electronic, or mechanical control signals.

In the alternative embodiment, a plurality of WGM resonator fiber segments are provided along a single optical fiber sufficiently close that each WGM resonator may be optically coupled longitudinally to its neighboring WGM resonators. A fiber-optic waveguide may be optically coupled to a first resonator fiber segment, and a second fiber-optic waveguide may be optically coupled to a second resonator fiber segment. Appropriate selection of a combination of resonant frequencies for each of the resonator fiber segments enables tailoring of the frequency dependence of the overall optical coupling between optical fiber and optical fiber via the plurality of resonator fiber segments. In this way optical power control devices having specifically designed/tailored frequency characteristics may be fabricated.

The alignment device, comprising one or more grooved and/or indexed alignment substrates, may be fabricated from a material sufficiently rigid to provide reliable, reproducible, and stable positioning of the fiber-optic waveguide, WGM resonator, and any secondary or modulator optical assembly that comprise the optical power control device. Preferred materials

may include ceramics or semiconductors such as silicon or a III-V semiconductor, but other material (such as metals, alloys, glasses, crystalline materials, and dielectric materials) may be employed while remaining within the scope of inventive concepts disclosed and/or claimed herein. The waveguide-alignment groove and the resonator-alignment groove may be formed by any suitable means for machining (or otherwise processing) the material used. A preferred method for providing the grooves is laser machining (most preferably ablative laser machining with an excimer laser), however, other fabrication techniques may be employed, such as lithographic patterning of a mask followed by wet (chemical) or dry (reactive ion) etching, electric discharge machining, plasma discharge machining, or single wire arc ablation. These same machining/processing techniques may be employed for providing other alignment and/or indexing structures on the alignment device (such as tabs, slots, pins, holes, grooves, and the like).

Laser machining has been set forth as a preferred method for spatially-selective removal of material from the optical fiber at various points in the fabrication process of fiber-optic waveguides and whispering-gallery-mode resonator (for patterning etch masks, deposition masks, diffusion and/or doping masks, and so forth). While remaining within the scope of inventive concepts disclosed and/or claimed herein, other methods for patterned removal of material from the optical fiber may be employed, including but not limited to: lithographic methods, optical patterning of photosensitive materials and/or photo-resists, mechanical techniques, electric or plasma discharge techniques, combinations thereof, and/or functional equivalents thereof.

The techniques encompassed by the term "cylindrical lithography" may be employed to produce fiber tapers that may in turn be employed for polarization-specific propagation of optical modes therethrough and evanescent coupling of such modes to the whispering-gallery optical modes of a WGM optical resonator. Cylindrical lithography may be employed to produce a non-PM tapered optical fiber segment coupled on each end thereof to PM optical fiber. The technique involves splicing a section of standard (i.e., non-PM) single-mode fiber into a length of PM fiber and heating/pulling the standard fiber segment to form the tapered section. The two opposing sections of PM fiber must be rotationally aligned to high precision (1° or better), which can be achieved by the following process: (1) determine the orientation of one segment of PM fiber by rotating it under planar illumination and measuring the scattering pattern as a function of angle

(i.e., measure the POL pattern of the fiber as is conventionally done in PM-capable fusion splicers); (2) fuse this section of PM fiber to a segment of standard single-mode fiber on which a portion of mask material such as hermetic carbon is provided; (3) translate the fiber to bring the opposing (free) end of the coated standard fiber segment into the lithography exposure apparatus, whilst preserving the angular orientation of the fiber; (4) employ the technique of cylindrical lithography to produce angular registration marks on coated section in the near proximity of the free end of the coated standard fiber segment; (5) measure the POL pattern of the second segment of PM fiber; (6) align the PM fiber with respect to the angular registration marks, and fuse the second PM fiber segment to the segment of standard fiber. This process would produce a fiber taper waveguide member appropriate for polarization selective coupling to a WGM resonator since minimal polarization randomization should occur for a propagating optical mode traversing the tapered segment, provided the spliced-in section of standard fiber is sufficiently short.

The present invention has been set forth in the forms of its preferred and alternative embodiments. It is nevertheless intended that modifications to the disclosed fiber-optic waveguides and methods of fabrication and use thereof may be made without departing from inventive concepts disclosed and/or claimed herein.